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## MAN'S THERMAL BALANCE IN SPACE ENVIRONMENTS

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With the completion of Project Mercury, the United States program for exploration of space faces a transition before the next major phase, flight to the moon, begins. Orbital flight is, in a sense, the first firm "step" into the space environment. Its successful accomplishment lends confidence for solution of problems of the transition phase, the Gemini program, which will establish a major need capability, orbital rendezvous. On this is predicated the next major phase, the Apollo program.

It is appropriate at this point to take a serious look at one of the crucial aspects of man's penetration of the space environment, that of maintaining the thermal balance between his body and his environment, on which his very life depends. Flight to the moon, and man's personal exploration of its surface, will impose problems of both design and reliability of performance considerably beyond those required in an orbital flight vehicle.

Reexamination of this problem is indicated for several reasons:

1. Problems of thermal control of the astronaut's environment have been present to some extent in most orbital flights to date.
2. Should an uncorrectable malfunction of environmental temperature control have occurred in any of the Mercury flights, termination was at least technically feasible within a time

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period reasonably consistent with man's tolerance of temperature extremes that might be expected, short of some catastrophic event such as loss of a heat shield.

3. Once a space vehicle has left Earth's orbit, and is in a trajectory to the moon (or farther), there is little or no possibility of quick emergency return to the Earth's surface as a means of escape from intolerable thermal overloads of the body. Right now there seem to be no firm plans for thermal "lifeboats," "ejection seats," or "escape capsules" in extra-terrestrial missions.
4. Even if no emergency should occur, threatening survival through strictly physiological thermal problems, it is urgent that the astronauts' thermal environment be as near optimal as possible, so that they may function with maximum (or at least adequate) efficiency in the exacting duties of the lunar mission.
5. It has taken man roughly half a century to develop the modern technology of thermal control of his earth-surface habitations to a point of even reasonable function and reliability. To compress the developmental cycle of equipment for thermal control in space vehicles and accessories, including space suits, into a period only one-tenth to one-fifth as long, and at the same time to achieve substantially 100 per cent reliability, is expecting a great deal. It is possibly expecting too much of fallible, even though intelligent, man?

#### OUR EXPERIENCE SO FAR

Let us look at what has so far been accomplished in this field, starting with the Air Force Man High Project.<sup>(1)</sup> In this project, balloons were used to lift man to near the "top" of the atmosphere, pending development of the technology of using rocket boosters for manned flight. The man's vehicle was an airtight capsule which was a functional forerunner of the rocket-boosted capsules of Project Mercury.

In June, 1957, Captain Joe Kittinger made the first Man High flight, to an altitude of 96,000 feet. While his capsule temperature did not reach dangerous levels, it was uncomfortably high. Because of an accidentally-reversed oxygen supply connection, Kittinger's flight had to be terminated much sooner than planned, to prevent his running out of life-giving oxygen.

In August, 1957, Captain David G. Simons reached an altitude of 102,000 feet in the second Man High flight, and remained near that altitude for over 32 hours. For a considerable part of the time, he was troubled with excessive temperature in the capsule. This was complicated by partial failure of his atmosphere regeneration system, and by his own stress-induced failure to take food when he should.

In October, 1958, Lieutenant Clifton McClure reached an altitude of 99,700 feet. Because of totally inadequate means of sensing the capsule atmosphere temperature, the first clue that things were not right was his own report that his body temperature was 101.4 degrees. Trouble was experienced in getting the balloon to descend, and before he landed McClure's internal body temperature had reached 108.5 degrees. That he did not suffer harm from this temperature, ordinarily considered to be in the near-lethal range, is phenomenal. He remained lucid all the way to earth, testimony to an inner strength and determination that would be found in few persons.

In the Navy Stratolab balloon flights of November 8, 1956 and October 18, 1957, which reached altitudes of 76,000 and 85,700 feet, and had durations of about 4 and 9 hours, respectively, gondola temperature-humidity values caused thermal stress. This was not acute, but coupled with the discomfort and limitation of action produced by the pressure suits, created an almost intolerable condition, as reported by Malcolm Ross.<sup>(2)</sup>

In the Mercury program, problems of human thermal control were present, to some extent, in most orbital flights. John Glenn experienced rather severe thermal stress, fortunately near- and post-landing, when it was not critical to his survival. Schirra's flight came near to being aborted at the end of the first orbital pass because of rising suit inlet temperature. Fortunately, he was able to make adjustments

which compensated for the malfunction, which was later traced to a valve orifice partially blocked by dried lubricant. However, during the flight, the face-plate of his helmet became partially smeared by perspiration, interfering with his vision.

In the final 22-orbit Mercury flight of 34 hour duration, Gordon Cooper experienced no serious thermal stress, but was found to be in a dehydrated condition post-flight, as will be discussed later.

### THE SPACE ENVIRONMENT

Let's take a good look at what we call the Space Environment, and its relation to the man.

Actually, this airless region is not the true environment of the man. It has a rather high flux of radiant energy from the sun, and is traversed by a fair number of high-velocity particles ranging from sub-atomic to macroscopic size. These and other characteristics have a great deal to do with how we design the vehicle and other equipment in which man will travel, and which will provide the atmosphere and other aspects of the environment directly affecting the man.

Since the announcement of man's serious intention to explore space, the characteristics of the external environment have been given a lot of attention. We have rigorously searched and documented what is known, and outlined research programs to get information on what is yet unknown. It is not my purpose to discuss this at any length or to try to present detailed information. Suffice to say that what we know is pretty well on record, though like much other information, this is not always easily or quickly found, or agreed upon among all researchers. What we don't know will become available in due time if we have planned wisely and have good fortune in our research programs.

We do need to know considerably more than we know now. One particularly needful area is the question of how true space environment affects the materials which will constitute man's prime physical protection when he gets out of his hard-shelled spacecraft and, for instance, explores the surface of the moon. Some recent findings regarding conventional materials used in spacesuits have not been reassuring.

We need to know much more precisely about the detailed physical characteristics of the moon's surface. We must also know a good deal about how the materials of the moon's surface (rock dust or whatever it may be) behave in the hard vacuum of space, in relation to man's protective suit and any vehicle he may try to operate on the moon. Preliminary experiments have shown that rock dust, in hard vacuum, behaves quite differently than in air, and tends to cling to itself and to other materials. Under the low gravitational force of the moon, about 1/6 of that on earth, this could prove to be quite a problem if we do not study it adequately beforehand. The surfaces of non-metallic and even metallic solid objects, made of materials whose characteristics we have thought we knew intimately and thoroughly, may have quite different characteristics when they have lost, in the ultra-hard vacuum of space, the clinging layer of gas molecules they possess in the earth's atmosphere.

The points just mentioned are obviously not, in themselves, thermal problems. However, they bear directly on the over-all problem of designing both the space vehicles and the personal protective equipment that man will wear both inside and outside the vehicles. If some of the information we need for proper design does not become available for several years, as is easily possible, this could directly affect the developmental cycle of this equipment. It could shorten the time in which design can be perfected and subjected to a long enough period of proof-testing and practical use to make sure that it is not only adequate, but also for practical purposes absolutely reliable.

With regard to knowledge of man's thermal relations with his environment, basic physiological knowledge is fairly good, but by no means complete. As an environmental physiologist, I still believe we need more research and development in this field. Of these two aspects, the need for development is probably greater--at least more urgent in relation to man's space ventures than the need for research.

#### ENVIRONMENTAL CONTROL PROBLEMS

I am particularly concerned with the system which will have the most direct effects on man's thermal balance in space environments, his space suit and its associated means of environmental control.

Although the capsule which will take man to the moon is being designed to provide, within itself, a "shirt-sleeve" environment, analysis of the activity cycle of the astronauts indicates that they may have to wear their pressure suits from one-third to possibly one-half of the estimated week or so of the lunar round-trip. Because of the limited space within the capsule, and the problems of putting on and taking off the suit in the weightless state, they may end up wearing the suits even a larger proportion of the time.

Without going into an extended discussion of the control of the atmosphere within the space capsule itself, this will involve some problems regarding which we still lack information. One is the possible (and probable) stagnation of the atmosphere under the weightless condition which will prevail most of the time. The circulation and mixing of air caused by temperature differentials in our normal earth surroundings, and between our body and the envelope of air in which it lives, depends completely on gravity. In a space vehicle under zero-G conditions, air in contact with a relatively warm surface, either of the body or of the vehicle, will not "rise," nor will air in contact with a cold surface "fall." Its density will change locally, but mixing with adjacent air, or with air at a distance, will result only through diffusion (about which we know little or nothing under weightless conditions), or through induced mechanical circulation.

So far as the man is concerned, because there will be no tendency for the air within his clothing, heated by his body, to rise by "chimney effect" as on the earth, he may have to wear lighter or less clothing, and seek an induced air current, though possibly reduced air or wall temperatures may help solve the problem. The point is, we are in an area where we just don't have the information even to determine our design parameters.

#### SPECIAL PROBLEMS IN THE SPACE SUIT

Let's look at the space suit problem as a whole.

A space suit obviously has to be absolutely pressure-tight and therefore impervious to air, except that intentionally ducted in and out. The man within will be almost completely dependent on circulation



of air through the suit, for control of his body temperature. (This discussion will be related almost solely to the problem of taking care of the body's need for heat loss, since warming the body is less of a problem and could be taken care of by supplementary electrical heating elements in the clothing, if necessary.)

This circulating air will have to do two jobs which the air in our ordinary environments has to do: (1) pick up heat by direct warming of the air itself (ordinarily called convective heat removal), and (2) pick up heat by evaporating water from the surface of the body (evaporative heat removal.) It will also have to compensate for the fact that since the suit has to have rather low thermal conductance, its interior temperature will also determine the radiant environment to which the man is exposed.

In ordinary, comfortable environments, radiative heat loss is a rather important part of our body temperature control process. In the space suit, the body will be able to radiate only to a surface which is likely to be rather near skin temperature. Therefore, radiative heat loss will be a relatively low proportion of the whole, throwing nearly the whole task on the suit-ventilation air.

Two other major problems must be solved in an optimum space suit design. One is the fact that when the man goes outside the space vehicle, into the full flux of the sun's radiant energy, one side will be exposed to a high radiant energy input, while the other will in effect be radiating to "cold space," or some portion of the moon's surface, or both. The surface heated by the radiant energy will not have air in contact with it, as on earth, to help remove heat. A supplementary means of limiting the amount of radiant energy reaching the surface of the suit proper may help to solve this problem. It may also be desirable to provide means for equalizing the thermal condition as between the shaded vs non-shaded side of the suit.

#### VARIABILITY OF HEAT PRODUCTION

The other major problem is that in comparison with the amount of heat produced by the body during minimal physical activity, as when sitting quietly, heat production can easily increase by a factor ranging

from 2 or 3 for mild activity, to 8 or 10 or more if heavy work has to be done. Fortunately, in the weightless state, or under the moon's low gravitational pull, the work of locomotion, and of performing routine tasks, will be substantially lessened. However, it is not impossible that in an emergency on the moon's surface, requiring repairs of the lunar landing vehicle, the astronaut might find it necessary or desirable to do considerable physical work. This could include lifting objects, within his normal strength capabilities, which on earth would weigh 6 times as much, up to perhaps a quarter-ton. Even though on the moon this would require a lifting effort of only about 100 pounds, his heat production could rise by a large factor.

The principal problem involved in this situation is that the body finds it necessary to throw off more heat, in order to maintain its core temperature within the normal or acceptable range, skin temperature tends to rise, and the sweat glands wet the skin to increase evaporative heat loss. This is a thermally effective process so long as the air in contact with the skin, by virtue of its relative dryness and movement over the surface, can evaporate the perspiration from all areas as rapidly as the sweat glands put it out.

If heat loss from the body is not thus brought into balance with heat production, both skin temperature and body core temperature will tend to rise, stimulating still greater sweat production. And if this sweat is not all evaporated at or near the body surface (in absorbent clothing, for instance), it will tend to run off and be wasted as a cooling agent.

#### PROBLEMS CAUSED BY WATER

It is quite difficult to reliably evaporate any considerable amount of sweat poured out by the body when it begins to become overheated in an impermeable garment. Under moderate to severe thermal conditions, sweat may be produced by the body at a rate ranging from one to as high as three pints an hour. Evaporating this from the surface of the body, by means of air flow ducted through the interior of an impermeable suit, is a rather formidable task. This involves not only the problem of sizing the ducting to handle enough air in the

gross, but also distributing it (and collecting it) over the various parts of the body. Not all surfaces produce sweat at the same rate. This complicates the ducting design problem, particularly with regard to effects on the bulk and mobility problems which are already a prime area of concern in space suit design.

If sweating has to be depended upon for body temperature control, the water which leaves the body causes problems not only with regard to its evaporation into the suit ventilation air stream, but also in the environmental control system which must process this air. This has been experienced in both the Man High and Mercury capsules. Need for removal of any considerable amount of water from the cabin or from suit-ventilating air both complicates design and may interfere with removal of carbon dioxide from the atmosphere. It may also disturb control of oxygen generation in certain chemical systems for environmental control.

From the physiological standpoint, loss of water from the body at an accelerated rate requires replacement by drinking. If this is not done before a certain point, the body's internal physico-chemical balance is disturbed, with consequent adverse effects on performance, both physical and psychological. It has been repeatedly established, both in the extensive scientific studies of sweating in desert environments, during World War II, and even in the Mercury flights, that adequate replacement of body water lost by sweating tends to be neglected, even when water is available. Astronaut Gordon Cooper ended his 34-hour space flight in Faith 7 in a dehydrated condition. This was in part due to the fact that he had to use one of his drinking water containers to store excessive water condensed from the environmental control system, and which was considered unsafe to drink. His weight loss of 7-3/4 lb during the flight was the difference between his body water loss and his intake by food and drinking. The latter was estimated at not over 3 pints, and should have been considerably more to prevent dehydration.

The penalties of dehydration become more severe the farther it goes. Some of its acute effects are:

1. Increased pulse rate;
2. Increased body temperature;
3. More rapid rate of breathing;
4. Appearance of tingling and numbness;
5. Reduced blood volume;
6. Blood becomes more concentrated, even "sludged;"
7. Nausea; lack of appetite;
8. Instability of emotions.

Exhaustion begins to show when water loss amounts to about 5 to 6 per cent of the body weight. After drinking enough water, relief is experienced in even a few minutes. However, it is much safer to avoid the dehydration by minimizing water loss, or if this is impossible, drinking even if one has to force himself to do so. If dehydration proceeds to about 12 per cent of the body weight or more, body core temperature may increase explosively, and sweating often stops. Actual damage to the nervous system, including the brain, occurs if body core or brain temperatures rise to about 110 to 112°F.

Present accepted practice in the design of space suits, and other ventilated garments, is to utilize the evaporative range of the human body's thermal control mechanism, since this minimizes the volume of gas which must be circulated through the suit in order to remove a given amount of heat. This is perhaps acceptable as a relatively short-term or emergency measure, if the environmental control system which must handle the circulating air is capable of removing the maximum water vapor outputs.

However, this must be considered as physiologically undesirable, since it could introduce a stress, possibly a rather significant one, at a time when this might combine with other stresses to seriously impair the functional capability of the man. For this reason, it would be preferable to design for minimum reliance on evaporative body cooling. Whether the solution lies in the direction of increased ventilation volumes, use of new principles such as thermoelectric cooling, or some other means of heat transfer, is up to the ingenuity of the designer.

### PHILOSOPHY OF DESIGN AS A FACTOR IN RELIABILITY

It should need no further emphasis that man's very life in space environments depends upon whether the control systems for the spacecraft and his space suit will maintain him in reasonable thermal balance, and that these systems must provide essentially 100 per cent reliability. How are we to achieve such reliability?

One thing we must recognize about much of the equipment for manned space flight is that it is almost in the category of "one-of-a-kind." This requires a somewhat different approach than mere reliance on the statistical systems which admittedly do a pretty good job under quantity-production conditions. An admirable guide to such systems has been made available by the S.A.E. in Volume 4 of the Technical Progress Series: "Reliability Control in Aerospace Equipment Development."

Many years ago, C. M. Ashley of the Carrier Corporation, in discussing the problem of perfectionism as an attitude in design engineers,<sup>(3)</sup> listed several precepts in the philosophy of design which could well be applied in the problem we are discussing. They are:

"First, trouble must be expected from any change, however small. Second, the likelihood of trouble increases with the magnitude and with the novelty of the change. Third, the chances of catching the trouble in the laboratory stage depend upon the extent and intelligence of the proof tests. Fourth, no amount of proof-testing will catch all of the troubles. Fifth, the wise general always lays his plans for a retreat before he starts his advance."

Although Ashley wrote this about two decades ago, the wisdom of his observations is borne out by current articles in the field of reliability assurance. In an article on the effect of modifications on reliability, Gurr<sup>(4)</sup> pointed out the insidious effects which accelerated schedules may have on programs of proof-testing for reliability. It is too often true, he said, that if a seemingly minor change is made in one component of a system, schedule-pressure sometimes results in only that component being re-tested after the change, and not the whole system. Because of interaction between components and systems, this could cause a failure which might have been forestalled if a test had been run.

### HUMAN ERROR FACTORS

B. J. Smith<sup>(5)</sup> has also aptly pointed out that in spite of most careful attention to reliability assurance techniques, human errors contribute from one-fifth to one-half of all system malfunctions. He also calls attention to the fact that: "...It is unproductive to try to arrive at system reliability as though the human and hardware subsystems could be characterized with the same statistics. You don't measure men by Mean Time to Failure, and you don't measure most machines by Variance, either within nor between machines." He further believes that: "...we may be overlooking some important human factors, such as motivation, honesty, vigilance, ordinarily thought of as a command rather than design functions."

The need for well-formulated and thorough programs of environmental testing, as a means of achieving high reliability, as well as some of its limitations, has recently been discussed by John H. Boeckel of the Goddard Space Flight Center.<sup>(6)</sup> He pointed out that: "...In general, the manned and military missions require a considerably higher degree of reliability than does the scientific one. Unreliability in a scientific satellite implies loss of data; in a manned satellite, 1 loss of life; and, in a military satellite, risk to the nation's defense posture."

With regard to use of mathematical models, Boeckel pointed out that mathematical prediction is only indicative; it helps to highlight those elements in an assembly having the greatest impact on system performance, but does not always enable accurate quantitative prediction. Regarding testing philosophy, he said: "...The variations between individual elements and the unpredictable interactions and dependencies that are the curse of accurate mathematical analysis tend to dominate the problem. Therefore, flight unit performance cannot be predicted statistically from the previous test results, and rigorous testing of the actual flight units becomes a necessity."

To sum up the argument:

1. Man's thermal balance in space can be just as critical to his survival and return to earth as reliable performance of his spacecraft's

propulsion, guidance, communication and other systems.

2. His safety can be assured by good design of essential equipment, in combination with reliability which comes as close to 100 per cent as anything we can achieve.

3. The necessary reliability will be achieved only by:

- a. Promptly acquiring all information basic to design;
- b. Establishing both basic and detail design as early as possible;
- c. Thorough proof-testing in realistic environments;
- d. Testing complete systems as well as components when any change is made;
- e. Avoiding change for a considerable period prior to critical use of a system;
- f. Giving a system a maximum of practical and rigorous use during the final validation period.
- g. Keeping in mind the fact that human factors in reliability are not yet susceptible of dependable statistical treatment and must receive attention through such non-statistical avenues as motivation, honesty and vigilance.

The deserts of the American West offer repeated testimony to the fact that if man lacks either the knowledge of its importance, or the equipment or procedures to maintain thermal balance, the penalty is ultimate. Let us see that the pioneers who represent us in coming trips into space have both the knowledge and the proper equipment.

It's a long way back from the moon.

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